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QUANTITY OF GASOLINE NECESSARY TO PRODUCE EXPLOSIVE CONDITIONS IN SEWERS

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ENGINEERING
NGIN STORAGE

BY

G. A. BURRELL AND H. T. BOYD

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QUANTITY OF GASOLINE NECESSARY TO PRODUCE EXPLOSIVE CONDITIONS IN SEWERS.

By G. A. Burrell and H. T. Boyd.

INTRODUCTION.

In connection with investigations relating to safety and efficiency in the production and utilization of petroleum and its products, the Bureau of Mines cooperated with the city of Pittsburgh, Pa., in a study of the causes of explosions in sewers and the means by which such explosions may be prevented. In this report are shown the quantities of gasoline that must be introduced into sewers in order to produce explosive mixtures of gasoline vapor and air under certain conditions. Many different factors govern explosibility, such as size of the sewer, velocity of the sewage, temperature of the sewer air, volatility and rate of inflow of the gasoline, so that only under identical conditions of tests would duplicate results be obtained.

The results herein published have a wider interest than the title of this paper implies, as they serve to show how leakage of gasoline in tunnels and in mine rooms or entries can cause disastrous explosions.

DESCRIPTION OF SEWER USED IN TESTS.

The particular sewer wherein the first tests here recorded were conducted is one of the largest in the city of Pittsburgh, Pa. It is 8 feet 3 inches wide and 8 feet 6 inches high. Figure 1 shows a plan of the sewer, with conditions such as existed when the first test was conducted. At *1*, *2*, *3*, *4*, *5*, and *6* are shown the manholes where samples of gas were collected. The distance from manhole *1*, where the gasoline was dumped into the sewer, to the sewer outlet, the Allegheny River, is 2,706 feet. The distances between the different manholes are shown on the figure.

The velocity of the sewage was established as follows: Pine floats 6 inches square were dropped into manhole *1* at a given signal. Stop watches were set at the same instant, and as the floats passed each succeeding manhole, as noted by a man standing at the foot of a ladder in each, the time was caught.

TEST 1. EFFECT OF RAPID ADDITION OF GASOLINE TO SEWAGE.

As a result of the determinations it was established that the average velocity of the sewage was 6.45 linear feet per second. The

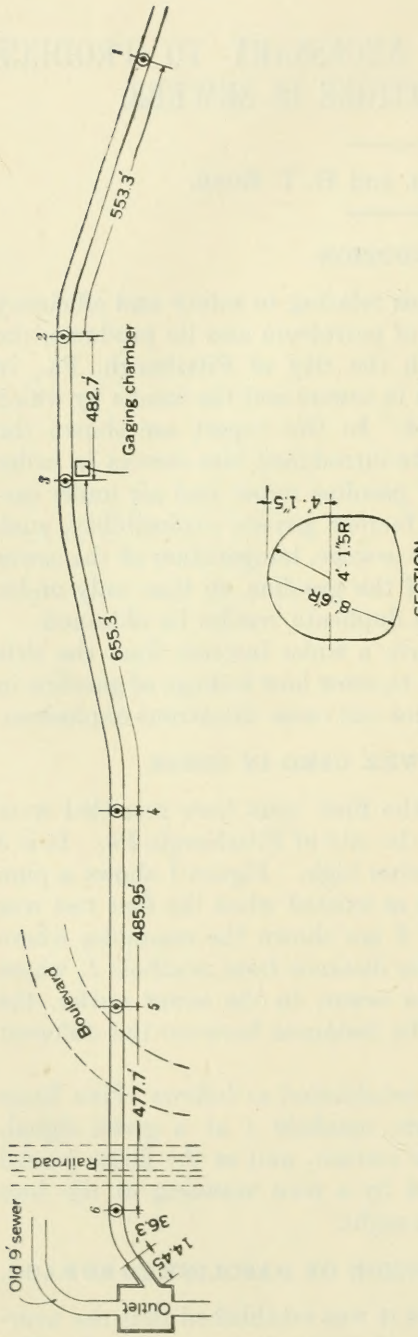

FIGURE 1.—Plan of sewer in which tests were conducted.

depth of the flow was about 8 inches, the amount of flow was 19.6 cubic feet per second, and the grade of the sewer was 0.90 per cent. The temperature of the water in the sewer was 21° C. (69.8° F.). The temperature of the air just above the water was 20.3° C. (68.5° F.) and of the air above ground was 20° C. (68° F.). At 2.10 p.m., 55 gallons of refinery gasoline, with a specific gravity of 67.5° B., was rapidly dumped from an open barrel into the sewer at manhole *1*. The barrel was simply turned on end and the gasoline dumped all at once.

Fractionation analysis of the gasoline used showed results as follows:

Results of fractionation analysis[a] of gasoline used in test 1.

Temperature, °C.	Percentage distilled over.
40[b]	1.46
50	3.4
60	7.0
70	13.0
80	20.5
90	29.5
100	41.7
110	54.5
120	65.5
130	76.5
140	84.0
150	91.0
160	97.5
Over 160	2.5
Total	99.4
Loss	0.6

COLLECTION OF SEWER-AIR SAMPLES.

Some samples of gas were collected by lowering ex-

[a] Made by M. S. Evans, director, bureau of tests, city of Pittsburgh.

[b] First drop distilled over at 31° C.

hausted glass sample tubes on the end of long poles and breaking off their tips by striking them against the sewer walls. The sewer air immediately rushed into the glass containers through the minute open-

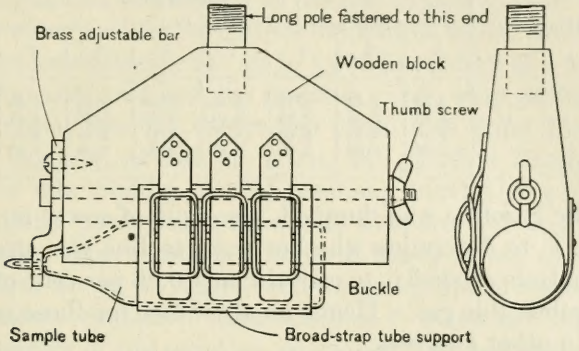

FIGURE 2.—Device for holding evacuated gas-sampling tubes.

ing thus afforded. Figure 2 shows the details of the device which was developed by M. S. Evans, director of the bureau of tests, city of Pittsburgh. The device was used for the first test. On the subse-

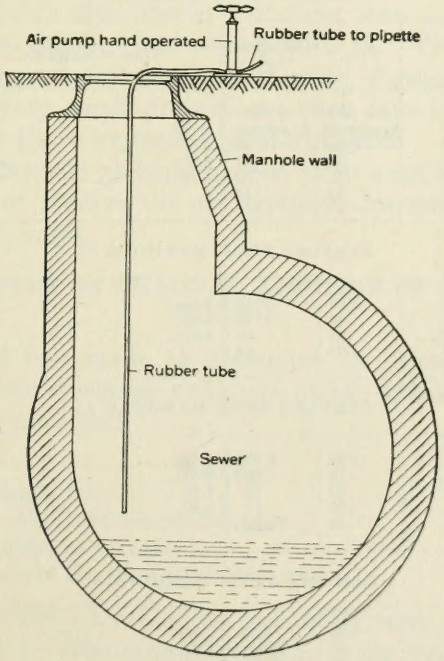

FIGURE 3.—Hand-operated pump and rubber tubing for collecting sewer-air samples.

quent tests samples of the sewer air were drawn from the sewer into bottles by means of a small pump with a long hose attachment (fig. 3).

Samples of sewer air were collected from 2.12 to 4.45 p. m. as follows:

Times at which samples of sewer air were collected.

Manhole No.—	Sample No.—								
	1	2	3	4	5	6	7	8	9
2	2.12	2.22	2.32	2.42	2.52	3.25	4.25	.....	.....
3	2.13	2.23	2.33	2.43	2.53	3.30	4.25	.....	.....
4	2.16	2.21	2.26	2.31	2.41	2.51	3.01	3.45	4.30
6	2.20	2.30	2.40	2.50	3.00	3.50	4.35	.....	.....

Before the gasoline was dumped, a sample of sewer air was taken at manhole *2*, to determine whether any gasoline was already in the sewer. Analysis showed it to contain only 0.06 per cent of CO_2 and a trace of combustible gas. Hence no allowance for those constituents was made in other analyses.

The analyses of the samples collected at the hours shown in the foregoing tabulation gave results as shown below. The methods of analysis used are discussed in a previous report issued by the bureau.[a]

Results of analyses of sewer air samples.

SAMPLES FROM MANHOLE *2*.[b]

Time of sampling.	CO_2.	Gasoline vapor.	Time of sampling.	CO_2.	Gasoline vapor.
p. m.	*Per cent by volume.*	*Per cent by volume.*	*p. m.*	*Per cent by volume.*	*Per cent by volume.*
2.12	0.05	0.89	2.52	0.08	0.136
2.22	.05	.27	3.25	.06	[b].01
2.32	.12	.25	4.25	Trace.	None.
2.42	.10	.18			

SAMPLES FROM MANHOLE *3*.[b]

2.13	0.05	2.19	2.53	0.06	[c] 0.01
2.23	.10	.23	3.30	.05	Trace.
2.33	.06	.10	4.25	.05	Trace.
2.43	.06	.04			

SAMPLES FROM MANHOLE *4*.[b]

2.16	0.08	0.672	2.51	0.05	Trace.
2.21	.10	.28	3.01	.10	None.
2.26	.07	.12	3.45	.05	None.
2.31	.05	.11	4.30	.05	None.
2.41	.05	Trace.			

SAMPLES FROM MANHOLE *6*.[b]

2.20	0.04	0.20	2.50	None.	None.
2.30	.05	Trace.	3.00		
2.40	.09	None.	3.45		
			4.35		

[a] Burrell, G. A., and Boyd, H. T., Inflammability of mixtures of gasoline vapor and air: Tech. Paper 115, Bureau of Mines, 1915. 18 pp.

[b] See fig. 1.

[c] Approximate.

GENERAL COMMENTS ON TEST 1.

One gallon of gasoline if entirely vaporized produces about 32 cubic feet of vapor at ordinary temperature and pressure. If 1.5 per cent of gasoline be adopted as the low explosive limit of mixtures of gasoline vapor and air, 55 gallons of gasoline would produce enough vapor to render explosive the air in 1,900 lineal feet of a 9-foot sewer, provided the sewer air and the gasoline vapor were perfectly mixed. It will be noted how far theoretical conditions differ from the conditions of the test, as follows: First, the gasoline flowing with the sewer water was rapidly carried past any particular point; second, only the lighter parts had a chance to evaporate at any point; and, third, gasoline vapor is about 3 times as heavy as air, so that mixing of vapor with air at an appreciable distance above the sewer water would be slow. Sample 1 from manhole *2*, taken two minutes after the introduction of the gasoline, contained 0.89 per cent of gasoline. Sample 1 from manhole *3* contained 2.19 per cent, and was taken three minutes after the gasoline had been poured in. In other words, the relation between the movement of the gasoline down the sewer, the distance between the manholes, and the time of collection of samples was such that at manhole *3* there was more gasoline vapor three minutes after the introduction than at manhole *2*, two minutes after the gasoline had been poured in. The significant fact is that 2.19 per cent was the largest quantity of gasoline vapor in any sample. Only very small proportions were found at any manhole 10 minutes after the introduction of the gasoline. It is evident that 1 barrel of gasoline (55 gallons) poured all at once in a manhole of a fast-flowing sewer renders the air explosive for only a few minutes at any particular point.

TEST 2. EFFECT OF GRADUAL ADDITION OF GASOLINE TO SEWAGE.

In the second test made to determine the quantity of gasoline necessary to render sewer air explosive under certain conditions, the following data were noted:

Test items.

Date of test, October 8, 1914.
Velocity of sewer water, 5.38 feet per second.
Amount of flow, 10.95 feet per second.
Area of flow surface, 31.53 square feet per second.

During test 2 the covers of the manholes were not removed, as was done in test 1. The hose connection to the pump was let down in some instances to within 2 inches of the sewer water and in other instances to within 2 feet. In test 2 the gasoline instead of being dumped into the sewer all at once, as in the first test, was allowed

to dribble down manhole *1* at the rate of 5 gallons per minute, 11 minutes being required for the barrel of 55 gallons to empty itself. The temperature of the sewer air at 11.40 a. m. was 68° F. (20° C.). The temperature of the outside air was 75° F. (24° C.). A sewer-air sample collected at manhole *2* before the gasoline had been poured in contained 0.20 per cent of carbon dioxide but no trace of combustible gas. The results of the analyses of samples of sewer air collected at the four manholes follow:

Results of analyses of sewer-air samples collected during test 2.

MANHOLE *2*.

Elapsed time after gasoline began to enter sewer.	Height of hose above water.	Percentage of gasoline vapor.	Elapsed time after gasoline began to enter sewer.	Height of hose above water.	Percentage of gasoline vapor.
Minutes.	*Inches.*		*Minutes.*	*Inches.*	
1½	2	0.26	13	2	1.14
3	2	1.01	18	24	.10
5	2	1.51	28	2	Trace.
7	24	.27	38	2	None.
9	2	1.07	48	24	None.
11	24	.12			

MANHOLE *3*.

3	2	1.28	14½	2	0.83
4½	2	1.63	19½	24	.16
6½	2	1.67	29½	2	Trace.
8½	24	.46	39½	24	None.
10½	2	1.17	49½	2	None.
12½	24	.40			

MANHOLE *4*.

4½	2	0.65	16	2	1.10
6	24	.55	21	24	.23
8	2	1.02	31	2	.12
10	24	.59	41	24	None.
12	2	1.13	51	2	None.
14	24	.70			

MANHOLE *6*.

6½	2	0.02	21	24	0.08
8	2	.06	26	2	.12
10	2	.13	36	24	Trace.
12	2	.05	46	2	Trace.
14	24	.25	51	24	None.
16	2	.45			

GENERAL COMMENTS ON TEST 2.

Some interesting results were obtained by alternately raising the hose from 2 inches to 2 feet above the water. As will be noticed, the highest percentage of gasoline obtained from the samples taken 2 feet above the water was only 0.70. It will also be noted that at any given point the sewer rapidly cleared itself of gasoline vapor.

Pouring in the gasoline required 11 minutes. Thirteen minutes after the inflow of gasoline had ceased there was, at manhole *2*, 2 inches above the water, 1.14 per cent of the vapor. Eighteen minutes after the inflow of gasoline, only a trace of vapor was left in the sewer air at that point. At manhole *4* the gasoline vapor was not swept out so quickly. In 16 minutes the amount was 1.10 per cent (2 inches above), and in 31 minutes 0.12 per cent. At certain periods, 2 inches above the water, dangerous atmospheres existed, but in all instances 2 feet above the water, the quantities discovered could not have propagated flame. Upon ignition of the gasoline at any time during a period of, say, 15 minutes after the gasoline had been dumped in a rapid sheet of flame would have swept along the sewer. The test shows, therefore, that 5 gallons of gasoline per minute introduced into the sewer under the conditions described would produce a dangerous condition as long as the flow lasted.

TEST 3. EFFECT OF SUBMERGING SEWER OUTLET.

In order to better understand what effect on the vaporization of gasoline from a sewer outlet would be produced by entire submergence of the outlet, such as by high water from the Allegheny River, test 3 was conducted on October 26, 1914. It was readily appreciated that the effect of having the sewer outlet submerged as suggested would be a slowing-up of the velocity of the sewage, and consequently with the same inflow of gasoline, there would result greater evaporation of gasoline in the sewer over a given length of time than if the gasoline were rapidly swept away by a fast current. In other words, there would be required a smaller quantity of gasoline to produce a dangerous condition, or the same quantity of gasoline would stay longer at a given spot.

To carry out the test a bulkhead was built in the sewer at manhole *3*, (fig. 1). Part of the flow was diverted into the old near-by sewer (fig. 1) by means of sandbags, and then the water in the sewer was allowed to back up gradually. The gasoline was dumped into manhole *2* (fig. 1) at the rate of 5 gallons per minute. Samples were taken at manholes *3*, *4*, *5*, and *6* (fig. 1) on a regular schedule, alternately 2 inches and 2 feet above the water, from 11.10 a. m. until 3.30 p. m. The results following were obtained.

Results of test to determine effect of submerging sewer outlet.

SAMPLES TAKEN AT MANHOLE *3*.

Time of taking sample.	Height of hose above water.	Percentage of gasoline vapor.	Time of taking sample.	Height of hose above water.	Percentage of gasoline vapor.
a. m.	*Inches.*		*p. m.*	*Inches.*	
11.10	2	1.47	1.00	24	0.10
11.20	24	.08	1.30	2	.10
11.30	2	.08	2.00	24	.13
12.00	24	.05	2.30	2	.12
			3.00	24	.14
p. m.			3.30	2	.20
12.30	2	.10			

SAMPLES TAKEN AT MANHOLE *4*.

a. m.			*p. m.*		
11.30	2	0.09	1.30	2	0.04
12.00	24	.12	2.00	24	.09
			2.30	2	.13
p. m.			3.00	24	.14
12.30	2	.07	3.30	2	.20
1.00	24	.11			

SAMPLES TAKEN AT MANHOLE *5*.

a. m.			*p. m.*		
11.30	2	0.86	1.30	2	0.63
12.00	24	.84	2.00	24	.53
			2.30	2	.55
p. m.			3.00	24	.50
12.30	2	.86	3.30	2	.68
1.00	24	.82			

SAMPLES TAKEN AT MANHOLE *6*.

a. m.			*p. m.*		
11.10	2	0.96	12.40	24	0.90
11.20	24	.76	1.00	2	1.05
11.30	2	1.15	1.30	24	.89
12.00	24	.95	2.00	2	1.02
			2.30	24	.36
p. m.			3.00	2	1.24
12.30	2	1.15	3.30	24	1.06

COMMENTS ON THE TEST.

The results of the test prove that with a sewer submerged by high water extremely dangerous conditions can result from a small amount of gasoline. As will be noted from the analyses, between manhole *5* and manhole *6*, a distance of about 500 feet, there was a dangerous condition five hours after the gasoline had been run in. It will also be observed that the percentages of gasoline were slightly but noticeably increasing at manholes *3* and *4* above. It can be readily seen that if, as might happen, a sewer should be submerged for several days or a week at a time a highly dangerous condition would result if as much as 5 gallons of gasoline or light oil were to escape at one point from garages and dry-cleaning establishments or other places situated on its drainage basin.

TEST 4. EXPLOSIVE EFFECT OF VARIOUS QUANTITIES OF GASOLINE ADDED TO SEWER.

The last of the four tests to determine the amount of gasoline vapor given off by varying quantities of gasoline in sewers was carried out November 6, 1914. Conditions were kept the same as in the third test, except that one-half the quantity of gasoline was used (27½ gallons), and samples were not taken until the gasoline had been entirely dumped. One-half barrel of gasoline was dumped into the sewer through manhole *2* (fig. 1) at 11.45 a. m., and every half hour, from 12 m. until 4.30 p. m., samples were collected at manholes *3*, *4*, *5*, and *6* (fig. 1). The samples were collected 2 inches and 2 feet above the surface of the water.

The results of the analysis are as follows:

Results of analyses of sewer-air samples taken in test 4.

Time.	Percentage of gasoline vapor at manhole—				Time.	Percentage of gasoline vapor at manhole—			
	3	4	5	6		3	4	5	6
m.					*p. m.*				
12.00	0.81	0.30	0.58	0.50	2.00	0.07	0.06	0.27	0.42
					2.30	.07	.02	.23	.39
p. m.					3.00	.08	.07	.22	.54
12.30	.07	.06	.35	.14	3.30	.08	.08	.18	.38
1.00	.08	.06	.36	.51	4.00	.09	.11	.21	.52
1.30	.08	.05	.33	.33	4.30	.08	.07	.14	.14

Several samples were taken at a manhole further up the sewer than where the gasoline was emptied. Two of the samples were analyzed with results as follows: Sample 1 contained 0.07 per cent of carbon dioxide (CO_2), and no gasoline; sample 2 contained 0.10 per cent of carbon dioxide, and no gasoline.

The samples were taken to ascertain whether the gasoline vapor has a tendency to travel up the sewer when the outlet is submerged. The results obtained with the two samples analyzed indicate that the vapor moved only a few feet up the sewer from the point where the gasoline entered.

The results of the analyses made in tests 3 and 4 indicate that the values of the analyses are almost in the same ratio as the quantities of gasoline used; for example, the samples collected on November 6, when one-half barrel of gasoline was used, showed approximately only one-half the percentage of gasoline vapor contained in the samples collected October 26, when one barrel of gasoline was used. The gasoline used for both tests was of the same grade. Consequently, one barrel would contain twice the volume of lighter hydrocarbons contained in one-half barrel, and when poured into the sewer should produce about twice as much vapor.

VAPOR PRESSURES OF DIFFERENT GRADES OF GASOLINE.

The volatility of gasoline, or its rate of evaporation, has an important bearing on its explosive effect when present in sewers. Gasoline of high volatility when dumped into a sewer evaporates much more rapidly, and, other things being equal, will make explosive a greater volume of sewer air than gasoline that is not so volatile. To determine the volatility, the vapor pressures of five different grades of gasoline were determined. The results are shown in figure 4. The determinations were made by introducing the gasoline into a 15-c. c. glass bulb connected with a mercury vacuum pump and a mercury manometer. First, the glass bulb containing the gasoline was cooled at a temperature of −78° C. (the temperature of solid carbon dioxide and acetone), and the air was removed from the system by means of the pump. At a temperature of −78° C. none of the gasoline samples had an appreciable vapor pressure. Next the bulb, with its gasoline, was surrounded by a bath, which was stirred and kept at constant temperature, and the pressure of mercury at different temperatures was noted. Before readings were taken, sufficient time was allowed for equilibrium to take place. Pressure readings could be made with an accuracy of ±1 millimeter of mercury, and temperature readings with an accuracy of ±0.2° C.

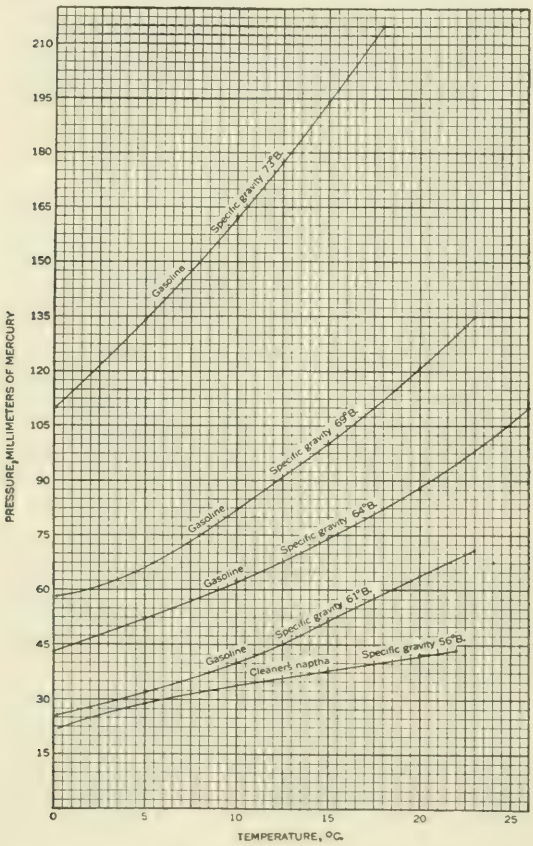

FIGURE 4.—Curves showing results of vapor-pressure determinations with five different grades of gasoline.

Much difference will be noted in the results. For instance, at the ordinary temperature of 17.5° C. the vapor pressure of cleaner's naphtha is 40 mm. of mercury; of 61° B. gasoline, 82 mm.; of 69° B. gasoline, 110 mm.; and of 73° B. gasoline, 212 mm. When these vapor pressures are expressed in terms of the percentages by volume

of gasoline vapor that will mix with air at the temperatures given, the results become—

Cleaner's naphtha, 40/760×100= 5.0 per cent.
64° B. gasoline, 82/760×100=11.0 per cent.
69° B. gasoline, 110/760×100=15.0 per cent.
73° B. gasoline, 212/760×100=28.0 per cent.

In other words, at a temperature of 17.5° C., air will uniformly mix with almost six times as much vapor from 73° B. gasoline as from cleaner's naphtha.

Gasoline is not a definite compound and the specific-gravity test is a poor criterion of the nature of a particular distillate; hence, the above figures only approximate what the vapor pressures of different gasoline distillates of the given specific gravities must be, but they show well enough, for the purpose desired, the relative danger of explosions from the different grades of gasoline when dumped into a sewer.

CITY INSPECTION OF SEWER AIR AT PITTSBURGH.

The city of Pittsburgh, because of two explosions, disastrous to property, in one of the sewers, began, as a result of cooperative work with the Bureau of Mines, a systematic inspection of sewer air, especially in the sewer where the explosions occurred. The sewer is about 96 inches in diameter at its beginning and 8 feet 10 inches at the outlet in the Allegheny River; the depth of flow varies from 12 inches to the entire cross section; the grade is 0.97 per cent; and the capacity at the outlet about 1,860 cubic feet per second. This sewer, which has a drainage basin of about 1,692 acres, drains a part of Pittsburgh that contains more automobile garages than any other part of the city. Four men were stationed along this sewer at different places equipped with apparatus with which they could make quick tests of the gasoline content of the sewer air at least once every half hour if necessary.

During a period of about one year 6,553 tests were made. Of these tests 6,278, or 95.8 per cent, showed less than 0.05 per cent of gasoline vapor in the sewer air; 205 tests, or about 3.13 per cent, showed between 0.05 and 0.1 per cent of gasoline vapor; 60 tests, or about 0.92 per cent, showed between 0.1 and 0.2 per cent of gasoline vapor; 6 tests, or about 0.09 per cent, showed between 0.2 and 0.4 per cent; and 4 tests, or 0.06 per cent, showed between 0.4 and 0.7 per cent gasoline vapor.

The tests showed that the ordinary flow from garages, cleaning establishments, and other sources of inflammable vapor was not enough to produce a dangerous condition in the sewer, that normally it was free of explosive gas. Only 4 tests out of the 6,553 showed about 0.5 per cent of gasoline vapor, whereas the explosive limit is close to 1.5 per cent. It was concluded, therefore, that the two

explosions were due to unusually large quantities of inflammable material being introduced into the sewer, and that such a condition only rarely prevails.

As a result of the cooperative work between the Bureau of Mines and the city of Pittsburgh, an inspection of the sewers is being continued by the bureau of tests, city of Pittsburgh, in order to watch for dangerous conditions and trace their cause to the source of the trouble if possible.

SUMMARY.

One barrel (55 gallons) of gasoline dumped at once into the sewer described caused the formation of an explosive mixture for a few minutes only at any given point. The explosive mixture was close to the surface of the sewer water and did not extend far into the upper sewer air.

When one barrel of gasoline was poured into the sewer at the rate of 5 gallons per minute the highest percentage of gasoline vapor 2 feet above the sewer water was 0.70 per cent. The highest percentage of gasoline vapor (2 inches above the sewer water) was 1.67 per cent. This was found at manhole *3* (fig. 1) 6½ minutes after the gasoline had been dumped into the sewer. Thirteen minutes after the inflow of gasoline had ceased there was (No. *2* manhole) 1.14 per cent of vapor 2 inches above the water. Eighteen minutes after the gasoline inflow had ceased only a trace of gasoline vapor was left in the sewer air at manhole *3*. At manhole *4* there was 0.12 per cent of vapor 31 minutes after the inflow had ceased. At certain periods of time, 2 inches above the water, explosive atmospheres existed, but 2 feet above the water the atmospheres were not explosive. Upon ignition of the gasoline at any time during a period of, say, 15 minutes after the gasoline had been dumped in, a rapid sheet of flame would have swept along the sewer.

When the sewer was bulkheaded to parallel conditions such as would prevail if the sewer outlet were submerged a dangerous condition resulted from dumping into the sewer at one point one barrel (55 gallons) of gasoline at the rate of 5 gallons per minute. At some places there existed a dangerous atmosphere 5 hours after the gasoline had been dumped in.

When one-half barrel (27½ gallons) of gasoline was dumped into the sewer at the rate of 5 gallons per minute there did not result at any time a dangerous condition, except during the first 15 minutes, when, although no samples were collected, the air-gasoline mixture was unquestionably explosive.

Out of the 6,553 tests of the air in sewers of the city of Pittsburgh, four, or about 0.06 per cent, contained as much as 0.4 to 0.7 per cent of gasoline vapor.

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